

# Descriptions of Carbon isotopes within relativistic Hartree-Fock-Bogoliubov theory

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Within the relativistic Hartree-Fock-Bogoliubov (RHFB) theory, the structure properties of Carbon isotopes are systematically studied. In order to reproduce the experiment data, we take the finite-range Gogny D1S with a strength factor  $f$  as the pairing force. The self-consistent RHFB calculations with density-dependent meson-nucleon couplings indicate the single-neutron halo structures in both  $^{17}\text{C}$  and  $^{19}\text{C}$ , whereas the two-neutron halo in  $^{22}\text{C}$  is not well supported. It is also found that close to the neutron drip line there exists distinct odd-even staggering on neutron radii, which is tightly related with the blocking effects and correspondingly the blocking effect plays a significant role in halo formation.

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## I. INTRODUCTION

During the past decades, the radioactive ion beams (RIBs) have greatly extended our knowledge of nuclear physics, from which are obtained the critical data for nuclear physics, astrophysics, as well as for testing the standard model. With worldwide and rapid development of RIB facilities, the investigations of the nuclear systems under extreme conditions generate new frontiers in nuclear physics. For example, the exotic nuclei [1–4] have fascinated more and more interests due to the unexpected exotic modes therein. One of the representatives is the nuclear halo structure characterized by a dilute matter distribution contributed by several (in general two) loosely bound valence neutrons (or protons) surrounding a condensed core, which was first found in  $^{11}\text{Li}$  [5]. As the typical light nuclei, the Carbon isotopes have been devoted many efforts to probing the possible halo structure [6–8] and specifically recent measured reaction cross section of  $^{22}\text{C}$  [9] seems to assert a new two-neutron halo structure, which has also attracted fairly large interests from the community [10–12].

In fact, the exotic modes keeping found in the weakly bound nuclear systems also bring serious challenges on the reliability of the nuclear theoretical models. When extending to the limit of stability of isotopes or isotones, the single neutron or proton separation energies become comparable to the pairing gap energy, such that the continuum effects can be easily involved by pairing correlations and play a significant role in determining the structure properties of exotic nuclei [13–15]. In terms of Bogoliubov quasi-particle, the relativistic Hartree-Bogoliubov (RHB) theory [15–17] has unified the descriptions of relativistic Hartree (RH) mean field and pairing correlations, and consequently the continuum effects are involved automatically. Since the first self-consistent description of nuclear halo structure in  $^{11}\text{Li}$  [13], the RHB theory has been successfully applied in predicting the giant halos in Ca [18, 19] and Zr [14, 19, 20] isotopes, as well as the restoration of relativistic symmetry [21] and superheavy magic structures [22].

With the inclusion of Fock terms in the mean field, the relativistic Hartree-Fock-Bogoliubov (RHFB) theory with

density-dependent meson-nucleon couplings [23] provides a new self-consistent platform for the exploration of exotic nuclei, e.g., predicting the giant halos in Cerium isotopes [19]. In addition, the inclusion of Fock terms has brought substantial improvements in the self-consistent description of nuclear shell structures [24] and the evolutions [25, 26], the relativistic symmetry restorations [24, 27, 28], and the low-energy excitation modes [29].

In this work, the structure properties of Carbon isotopes, particularly the possible halo structures therein, will be studied systematically within the RHFB and RHB theories. The contents are organized as follows. In the Sec. II, we introduce the general formalism of the RHFB equations with finite range (Gogny) pairing force. In Sec. III the discussions are concentrated on the halo structures and odd-even staggering (OES) of Carbon isotopes. Finally, a brief summary and Perspectives are given in Sec. IV.

## II. THEORETICAL FRAMEWORK AND NUMERICAL DETAILS

As generally recognized, the nucleon-nucleon interactions are mediated by the exchanges of mesons and photons. Based on that, the model Lagrangian contains the system degrees of freedom associated with the nucleon  $\psi$ , isoscalar scalar  $\sigma$ -meson, isoscalar vector  $\omega$ -meson, isovector vector  $\rho$ -meson, isovector pseudo-scalar  $\pi$ -meson and the photon ( $A$ ) fields [24, 30]. Following the standard variational procedure, one can get the equations of motion for nucleons, mesons, and photons, namely the Dirac, Klein-Gordon, and Proca equations, as well as the continuity equation for energy-momentum tensor, from which is derived the system Hamiltonian. In the terms of the creation and annihilation operators ( $c_\alpha^\dagger, c_\alpha$ ) defined by the stationary solutions of the Dirac equation, the Hamiltonian operator can be expressed as

$$H = \sum_{\alpha\beta} c_\alpha^\dagger c_\beta T_{\alpha\beta} + \frac{1}{2} \sum_{\alpha\alpha'\beta\beta'} c_\alpha^\dagger c_\beta^\dagger c_{\beta'} c_{\alpha'} \sum_\phi V_{\alpha\beta\alpha'\beta'}^\phi, \quad (1)$$

where  $T_{\alpha\beta}$  is the kinetic energy and the two-body terms  $V_{\alpha\beta\alpha'\beta'}^\phi$  correspond with the meson- (or photon-) nucleon cou-

plings denoted by  $\phi$ ,

$$T_{\alpha\beta} = \int d\mathbf{r} \bar{\psi}_\alpha(\mathbf{r})(-i\boldsymbol{\gamma} \cdot \boldsymbol{\nabla} + M)\psi_\beta(\mathbf{r}), \quad (2)$$

$$V_{\alpha\beta\alpha'\beta'}^\phi = \int d\mathbf{r} d\mathbf{r}' \bar{\psi}_\alpha(\mathbf{r}) \bar{\psi}_\beta(\mathbf{r}') \Gamma_\phi(x, x') \times D_\phi(\mathbf{r}, \mathbf{r}') \psi_{\beta'}(\mathbf{r}') \psi_{\alpha'}(\mathbf{r}). \quad (3)$$

In above equations,  $\Gamma_\phi(x, x')$  represent the interaction matrices associated with the  $\sigma$ -scalar,  $\omega$ -vector,  $\rho$ -vector,  $\rho$ -tensor,  $\rho$ -vector-tensor,  $\pi$ -pseudo-vector and photon-vector couplings, and  $D_\phi(\mathbf{r}, \mathbf{r}')$  denotes relevant meson (photon) propagator, and  $M$  is the nucleon mass (for details see Refs. [23, 24, 30]).

Standing on the level of relativistic Hartree-Fock (RHF) approach, the contributions from the negative energy states in the Hamiltonian (1) are neglected as usual, i.e., the so-called no-sea approximation [30]. The Hartree-Fock ground state  $|\Phi_0\rangle$  is then determined and consequently is derived the energy functional  $E$ , i.e., the expectation of Hamiltonian with respect to  $|\Phi_0\rangle$ ,

$$|\Phi_0\rangle = \prod_{i=1}^A c_i^\dagger |0\rangle, \quad E = \langle \Phi_0 | H | \Phi_0 \rangle, \quad (4)$$

where the index  $i$  denotes the positive energy states and  $|0\rangle$  is the vacuum state. In the energy functional  $E$ , the two-body interactions  $V_\phi$  lead to two types of contributions, i.e., the direct (Hartree) and exchange (Fock) terms. Within RHFB [23], the mean field part contains both types of the contributions, i.e., the RHF approach [31], whereas within RHB the Fock terms are neglected just for simplicity.

For the open-shell nuclei, the pairing correlations, which lead to valence particles spreading over the orbits around the Fermi level, have to be taken into account. Different from simple BCS method [32], the Bogoliubov theory can unify the descriptions of mean field and pairing correlations in terms of Bogoliubov quasi-particles. It is of special significance in exploring the nuclei far from the  $\beta$ -stability line where the continuum effects become essential and the simple BCS method may beak down. In the prior studies with both RHB and RHFB theories, it is already demonstrated that the scattering of the Cooper pairs into the continuum plays an essential role in the formation of the halo structures [13, 14, 19].

Following the standard procedure of the Bogoliubov transformation [33, 34], the RHFB equation can be derived as,

$$\int d\mathbf{r}' \begin{pmatrix} h(\mathbf{r}, \mathbf{r}') - \lambda & \Delta(\mathbf{r}, \mathbf{r}') \\ \Delta(\mathbf{r}, \mathbf{r}') & -h(\mathbf{r}, \mathbf{r}') + \lambda \end{pmatrix} \begin{pmatrix} \psi_U(\mathbf{r}') \\ \psi_V(\mathbf{r}') \end{pmatrix} = E \begin{pmatrix} \psi_U(\mathbf{r}) \\ \psi_V(\mathbf{r}) \end{pmatrix}, \quad (5)$$

where  $\psi_U$  and  $\psi_V$  are the quasi-particle spinors and the chemical potential  $\lambda$  is introduced to keep the particle number on the average. For the single-particle Hamiltonian  $h(\mathbf{r}, \mathbf{r}')$ , it consists of three parts, i.e., the kinetic energy  $h^{kin}$ , local potential

$h^D$  and non-local one  $h^E$ ,

$$h^{kin}(\mathbf{r}, \mathbf{r}') = [\boldsymbol{\alpha} \cdot \mathbf{P} + \beta M] \delta(\mathbf{r} - \mathbf{r}'), \quad (6a)$$

$$h^D(\mathbf{r}, \mathbf{r}') = [\Sigma_T(\mathbf{r})\gamma_5 + \Sigma_0\mathbf{r} + \beta\Sigma_S\mathbf{r}] \delta(\mathbf{r} - \mathbf{r}'), \quad (6b)$$

$$h^E(\mathbf{r}, \mathbf{r}') = \begin{pmatrix} Y_G(\mathbf{r}, \mathbf{r}')Y_F(\mathbf{r}, \mathbf{r}') \\ X_G(\mathbf{r}, \mathbf{r}')X_F(\mathbf{r}, \mathbf{r}') \end{pmatrix}. \quad (6c)$$

Detials are referred to Refs. [23, 30]. The pairing potential in the RHFB equation (5) reads as

$$\Delta_\alpha(\mathbf{r}, \mathbf{r}') = -\frac{1}{2} \sum_\beta V_{\alpha\beta}^{pp}(\mathbf{r}, \mathbf{r}') \kappa_\beta(\mathbf{r}, \mathbf{r}'), \quad (7)$$

with the pairing tensor  $\kappa$

$$\kappa_\alpha(\mathbf{r}, \mathbf{r}') = \psi_{V_\alpha}(\mathbf{r})^* \psi_{U_\alpha}(\mathbf{r}'). \quad (8)$$

For the pairing interaction  $V^{pp}$ , it is generally taken as a phenomenological form with great success in RHB theory [16, 35] and conventional HFB theory [36, 37]. In this work, we utilize the finite-range Gogny force D1S [38] with additional strength factor  $f$  as the effective pairing interaction,

$$V(\mathbf{r}, \mathbf{r}') = f \sum_{i=1,2} e^{((r-r')/\mu_i)^2} (W_i + B_i P^\sigma - H_i P^\tau - M_i P^\sigma P^\tau), \quad (9)$$

where  $\mu_i, W_i, B_i, H_i, M_i (i = 1, 2)$  are the Gogny parameters.

Due to the numerical difficulties originating from both RHF mean field and finite-range pairing interactions, the integro-differential RHFB equation (5) is solved by expanding the quasi-particle spinors on the Dirac Woods-Saxon (DWS) basis [39], which can provide appropriate asymptotic behaviors for weakly bound nuclei. For the calculations of Carbon isotopes, the DWS basis parameters are taken as follows: the spherical box-size is fixed to 30 fm and consistently the numbers of basis states with positive and negative energies are chosen as 48 and 12, respectively.

### III. RESULTS AND DISCUSSION

In this work, we calculated the Carbon isotopes from  $^{10}\text{C}$  to  $^{22}\text{C}$  by the RHFB theory with the effective interactions PKA1 [24], PKO2 [25] and PKO3 [25], and by the RHB theory with PKDD [40] and DD-ME2 [41]. For the odd Carbon isotopes, the blocking effects are taken into account. In practice, several orbits around the Fermi surface are blocked separately and

TABLE I: Blocked neutron ( $\nu$ ) orbits for odd Carbon isotopes in the calculations of PKA1, PKO2 PKO3, PKDD and DD-ME2.

	$^{15}\text{C}$	$^{17}\text{C}$	$^{19}\text{C}$	$^{21}\text{C}$
PKA1	$\nu s_{1/2}$	$\nu s_{1/2}$	$\nu d_{5/2}$	$\nu s_{1/2}$
PKO2	$\nu d_{5/2}$	$\nu s_{1/2}$	$\nu s_{1/2}$	$\nu s_{1/2}$
PKO3	$\nu d_{5/2}$	$\nu s_{1/2}$	$\nu s_{1/2}$	$\nu s_{1/2}$
PKDD	$\nu s_{1/2}$	$\nu s_{1/2}$	$\nu s_{1/2}$	$\nu s_{1/2}$
DD-ME2	$\nu s_{1/2}$	$\nu s_{1/2}$	$\nu s_{1/2}$	$\nu s_{1/2}$

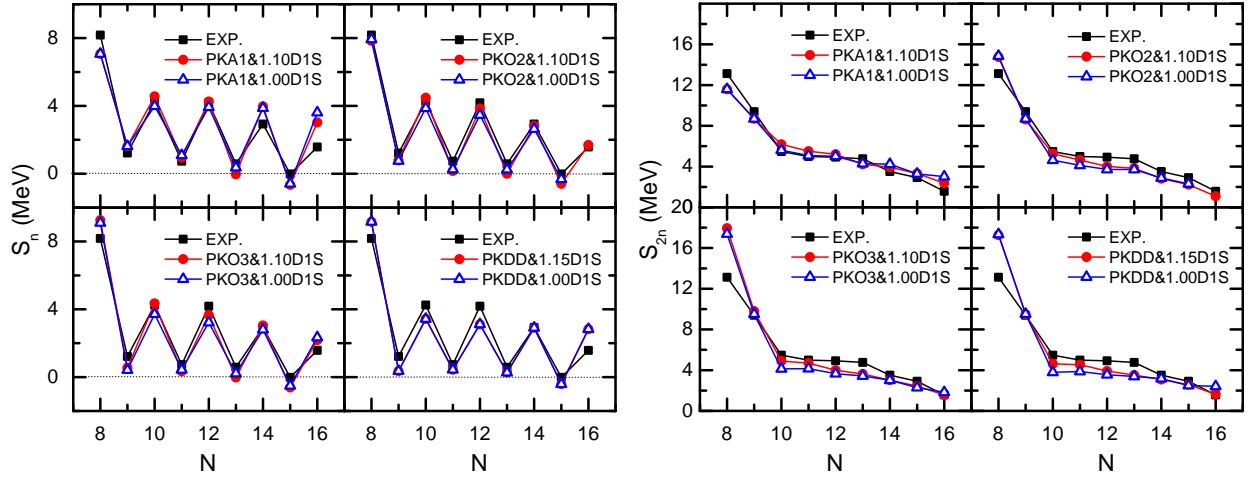


FIG. 1: (Color online) Single- ( $S_n$ ; left panels) and two-neutron ( $S_{2n}$ ; right panels) separation energies for Carbon isotopes from  $^{14}\text{C}$  to  $^{22}\text{C}$ . The results are calculated by the density-dependent RHF with PKA1, PKO2 and PKO3, and by density-dependent RHB with PKDD. The filled circles and open up-triangles denote the results calculated by taking the Gogny force D1S with/without prefix strength factor as the effective pairing interactions, respectively. As the references, the data extracted from Ref. [43] are shown in filled squares.

TABLE II: The mean square deviation from the data [43] for the binding, single- and two-neutron separation energies of the Carbon isotopes. The results are extracted from the calculations by PKA1, PKO2 PKO3, PKDD and DD-ME2 with different pairing strength factor  $f$ .

$f$	PKA1			PKO2			PKO3			PKDD			DD-ME2		
	$B$	$S_n$	$S_{2n}$	$B$	$S_n$	$S_{2n}$	$B$	$S_n$	$S_{2n}$	$B$	$S_n$	$S_{2n}$	$B$	$S_n$	$S_{2n}$
1.00	1.34	0.88	0.81	2.14	0.43	1.02	2.10	0.65	1.66	2.83	0.78	1.72	3.00	0.97	1.92
1.10	1.58	0.78	0.75	1.78	0.41	0.84	1.35	0.59	1.72	2.46	0.65	1.59	2.49	0.78	1.71
1.15	1.71	0.95	1.10	1.43	0.46	0.80	0.90	0.62	1.79	2.17	0.63	1.52	2.29	0.63	1.68
1.20	2.08	1.03	1.22	1.02	0.55	0.81	0.51	0.69	1.80	1.81	0.66	1.48	1.90	0.64	1.73
1.25	2.60	1.14	1.34	0.65	0.67	0.99	0.67	0.79	1.79	1.38	0.72	1.57	1.45	0.68	1.80

the strongest binding leads to the ground state [42]. In table I are shown the blocking configurations for the odd Carbon isotopes.

Figure 1 presents the single-neutron separation energies  $S_n$  (left panels) and two-neutron ones  $S_{2n}$  (right panels) of Carbon isotopes calculated with PKA1, PKO2, PKO3, and PKDD as compared to the data (in filled squares) [43]. The results calculated by DD-ME2 are omitted because similar systematics are found as PKDD. To get appropriate pairing effects, the comparison is performed between the results by taking the effective pairing force as Gogny force D1S (open up-triangles) and the one with the additional strength factor  $f$  (filled circles). From Fig. 1 one can find that the modification on the pairing force brings some systematical improvements on both single- and two-neutron separation energies, especially in the vicinity of drip line. The optimized strength factors are determined from the agreement with the data on the single-neutron separation energies as shown in Table II. It is seen that the systematics on single- and two-neutron separation energies are somewhat improved with the introduction of the strength factor. Specifically with the original Gogny D1S, PKO2 can not reproduce the drip line  $^{22}\text{C}$  which becomes bound with enhanced pairing force (see Fig. 1). In Table II it is also shown that the calculations with PKO2 provide the best agreements with the data on both  $S_n$  and  $S_{2n}$ , which may imply the most

reliable systematics. Therefore we utilize PKO2 as the representative to analyze the structure properties of Carbon isotopes.

Aiming at the possible halo structure in Carbon isotopes, Fig. 2 shows neutron and proton density distributions for even (a) and odd (b) Carbon isotopes. As shown in Fig. 2(a), it seems that the neutron densities tend to be more and more diffuse while not distinct enough to support the occurrence of halo structure, when close to the drip line. In fact the two-neutron separation energy of the  $^{22}\text{C}$  is 1.56 MeV from the recent data [43], which suggests that the last two valence neutrons are still bound too deep to spread over a fairly wide range. Hence  $^{22}\text{C}$  may not be a good candidate of well-developed two-neutron halo structure. Whereas in Fig. 2 (b) distinct evidence is presented for the halo occurrences in  $^{17}\text{C}$  and  $^{19}\text{C}$ , which represent much more diffused neutron distributions than  $^{22}\text{C}$ . In fact, the strong evidence of the halo in  $^{19}\text{C}$  can be found from the parallel momentum distribution of  $^{18}\text{C}$  after the breakup of  $^{19}\text{C}$  [6]. As shown in Fig. 1 nearly zero single-neutron separation energies of  $^{17}\text{C}$  and  $^{19}\text{C}$  can also be treated as another evidence for the existence of single-neutron halo structure. While for  $^{21}\text{C}$  the negative value of  $S_n$  leads to a diverged matter distribution, which might not be a bound nuclear system.

To further illustrate the halo occurrence, Fig. 3(a) presents

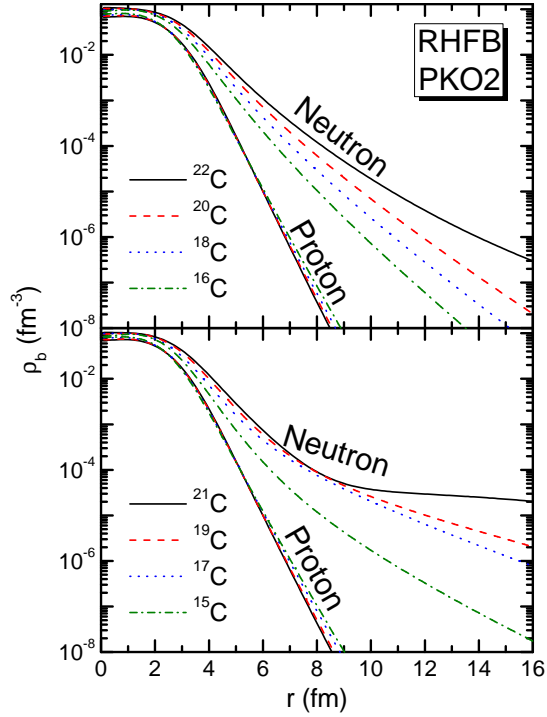


FIG. 2: (Color online) Neutron and proton density distributions for even [Fig. (a)] and odd [Fig. (b)] Carbon isotopes. The results are calculated by density-dependent RHFB with PKO2 and the pairing strength factor is adopted as  $f = 1.1$ .

the contributions of the neutron density from different orbits. It is clearly shown that the dilute matter distribution at large radial distance is dominated by low- $j$  state  $2s_{1/2}$  and the continuum, in accordance with the evidence of halo occurrences in  $^{11}\text{Li}$  [13] and Ca isotopes [18]. Consistently Fig. 3(b) presents another direct evidence, i.e., the number of neutrons  $N_{R>r}$  located beyond the sphere with radius  $r$ . From Fig. 3(b) it can be deemed that there exist evident single-neutron halo structures in  $^{17}\text{C}$  and  $^{19}\text{C}$  due to fairly large amount of neutrons spreading far beyond the neutron radii  $r_n$ . In contrast the values of  $N_{R>r}$  in  $^{18}\text{C}$  and  $^{20}\text{C}$  drop sharply with the increase of radius  $r$ , consistent with the neutron distributions shown in Fig. 2. Combining with the results in Fig. 3(a), one can find that both canonical state  $2s_{1/2}$  and the continuum present substantial contributions in the formation of halo, while dominated by the formal one due to its zero centrifugal barrier.

As the complementary evidence, Fig. 4 shows the neutron canonical single-particle energies for the Carbon isotopes from  $^{15}\text{C}$  to  $^{22}\text{C}$ . In Fig. 4 the ultra thick bars denote the occupation probabilities of each orbit. From Fig. 4 one can find that the valence orbits  $2s_{1/2}$  and  $1d_{5/2}$  are close to each other, which correspond to a fairly high level density and therefore induces strong pairing effects. Although both valence orbits are rather close to the continuum limit, the self-consistent RHFB and RHB calculations only support  $^{17,19}\text{C}$  as the candidates of halo nucleus instead of even drip line isotope  $^{22}\text{C}$ , which can be well interpreted by the blocking effects. In  $^{17,19}\text{C}$  the neutron quasi-particle states  $1s_{1/2}$  are blocked

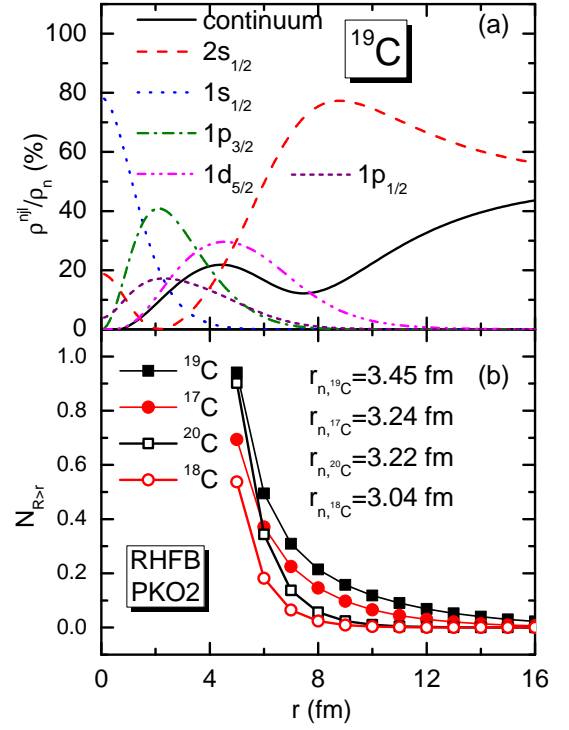


FIG. 3: (Color online) (a) Contributions to neutron density ( $\rho_n$ ) from canonical neutron orbits ( $\rho_n^{lj}$ ) and continuum states for  $^{19}\text{C}$ , and (b) neutron numbers ( $N_{R>r}$ ) beyond the sphere with radius  $r$  for  $^{17}\text{C}$ ,  $^{18}\text{C}$ ,  $^{19}\text{C}$  and  $^{20}\text{C}$ . The results are extracted from the calculations of density-dependent RHFB with PKO2.  $r_{n,17\text{C}}$ ,  $r_{n,18\text{C}}$ ,  $r_{n,19\text{C}}$  and  $r_{n,20\text{C}}$  denote the root mean square neutron radii of  $^{17}\text{C}$ ,  $^{18}\text{C}$ ,  $^{19}\text{C}$  and  $^{20}\text{C}$ , respectively.

and the corresponding contributions are mainly mapped to the canonical single-particle orbit  $2s_{1/2}$ . Different from the even isotopes, the neutron staying on the canonical orbit  $2s_{1/2}$ , mainly mapped from the odd-neutron on the quasi-particle state  $1s_{1/2}$ , then becomes much less bound due to lacking the extra binding from pairing correlations which is also illustrated from  $S_n$  in Fig. 1(a). As a result, the probability density of the valence state  $2s_{1/2}$  tends to be much diffuser than those in even isotopes to develop the halo structure in  $^{17,19}\text{C}$ . In fact due to the blocking of  $s$  orbit, the continuum effects are also enhanced in odd isotopes because the neutrons occupied  $d_{5/2}$  orbit can be only scattered into the continuum by pairing correlations.

As we know, the pairing correlations play significant roles for the halo occurrences in the even nuclear systems, not only in stabilizing nuclide itself but also in developing the halos by scattering the cooper pairs into the low-lying  $s$  or  $p$  orbits. The typical examples are  $^{11}\text{Li}$ , the drip line isotopes of Ca, Zr and Ce. While for the even Carbons particularly  $^{22}\text{C}$  it seems that the extra binding from the pairing correlations makes  $s$  orbit too bound to get dilute matter distribution. On the contrary, the odd neutron in  $s$  orbit presents substantial contribution in the formation of halo structure, which can be seen from the odd-even staggering (OES) on the neutron radius. Figure 5 (a) shows the neutron root mean square radii from  $^{14}\text{C}$  to  $^{22}\text{C}$

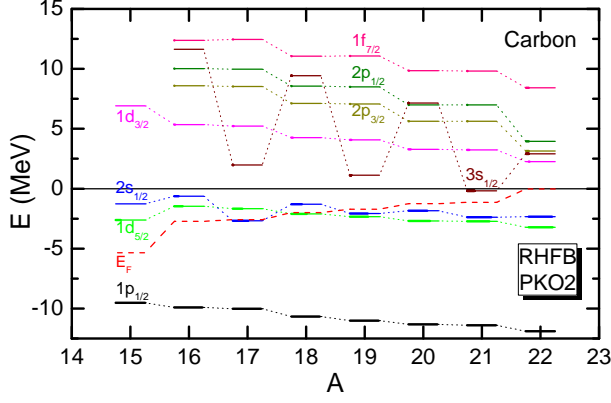


FIG. 4: (Color online) Canonical neutron single-particle energies for Carbon isotopes. The results are extracted from the density-dependent RHFB calculations with PKO2. The length of thick bars denotes the occupation probabilities of neutron orbits and  $E_F$  in short dashed lines represent the Fermi energies.

extracted from the calculations with PKA1, PKO2, PKO3 and PKDD. It is clearly shown that all the selected effective interactions except PKA1 present distinct OES on the neutron radius. Specifically, as seen from Fig. 5 (b), such OES is determined by the valence orbits  $2s_{1/2}$  and also depends on whether the corresponding Bogoliubov quasi-particle  $s$  orbit is blocked or not. In practice the orbits around the Fermi surface of the neighboring even isotopes are blocked separately and the blocking configuration is then determined as the one leading to the strongest binding, i.e., the ground state. From table I one can find that the blocking configurations are consistent with the OES in Fig. 5. In  $^{15}\text{C}$  which has larger neutron radius than  $^{16}\text{C}$  in the calculations with PKA1 and PKDD, the quasi-particle  $s$  orbit is blocked. Due to similar reason and consistently with the halo occurrence, the neutron radii of halo nuclei  $^{17,19}\text{C}$  are distinctly larger than the even neighbors. Different from PKO2, PKO3 and PKDD, PKA1 in fact does not support the halo occurrence for  $^{19}\text{C}$  in which  $d_{5/2}$  is blocked for the odd neutron and due to the pairing effects the neutrons occupied in the low- $j$  state, i.e., the  $s$  orbit, are bound too deep to distribute extensively.

It is well known that pairing correlation plays an important role in stabilizing the finite nuclei, especially the exotic ones. For  $^{11}\text{Li}$ ,  $\text{Ca}$ ,  $\text{Zr}$ , and  $\text{Ce}$  isotopes, it is already demonstrated that the pairing correlations show positive effects in both stabilizing and developing the halo structures. While in the RHFB (except PKA1) and RHB calculations of  $^{17,19}\text{C}$ , the quasi-particle  $s$  orbit is blocked and the corresponding contributions are mainly mapped to the canonical orbit  $2s_{1/2}$ , which plays the dominate role in the formation of single-neutron halo structure of  $^{17,19}\text{C}$ . This implies that the unpaired odd neutron may also contribute to develop the halo structure when it is not so deeply bound. In fact from the analysis above it is just due to the lack of extra binding from the pairing correlations that the odd-neutron can spread over far beyond the center of nucleus.

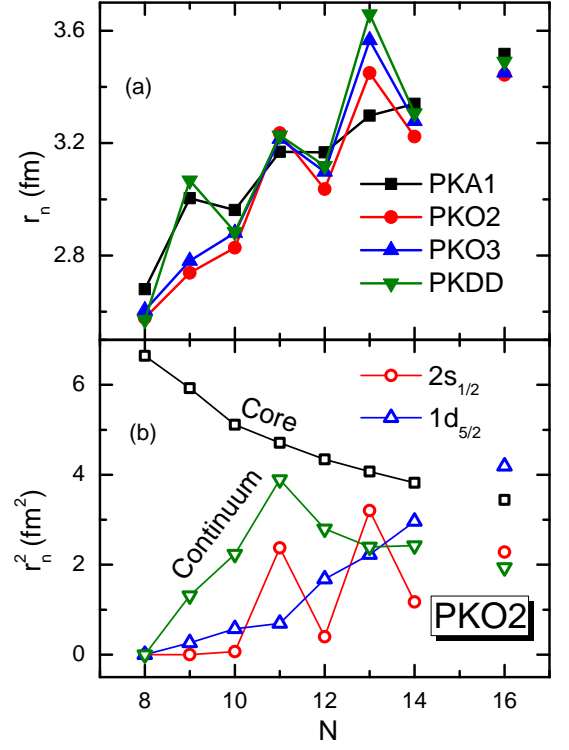


FIG. 5: (Color online) (a) Neutron root mean square radii calculated by density-dependent RHFB with PKA1, PKO2 and PKO3, and by density-dependent RHB with PKDD, and (b) contributions from the core orbits ( $1s_{1/2}$ ,  $1p_{3/2}$  and  $1p_{1/2}$ ), valence orbits ( $2s_{1/2}$  and  $1d_{5/2}$ ) and the continuum. The results are provided by the calculations of density-dependent RHFB with PKO2.

#### IV. SUMMARY AND PERSPECTIVES

In this work we have systematically calculated the ground-state properties of Carbon isotopes using the density-dependent relativistic Hartree-Fock-Bogoliubov (RHFB) theory with PKA1, PKO2 and PKO3 as well as the density-dependent relativistic Hartree-Bogoliubov (RHB) theory with PKDD and DD-ME2. It is shown that neutrons in the  $2s_{1/2}$  state in  $^{17}\text{C}$  and  $^{19}\text{C}$  are weakly bound and direct evidences are obtained for the single-neutron halo occurrences in the odd Carbon isotopes  $^{17}\text{C}$  and  $^{19}\text{C}$ . In addition, the self-consistent density-dependent RHFB calculations do not support two-neutron halo structure in  $^{22}\text{C}$ , disagreeing with the indications of the experimental reaction cross section measurement [9]. Pairing correlation is one of the important stability mechanisms of finite nuclear systems, and the blocking effect accompanying with it also plays a significant role in determining micro structure for odd-A nuclei. In this work, because of the blocking effect, the neutrons in the  $2s_{1/2}$  state in  $^{17}\text{C}$  and  $^{19}\text{C}$  are unpaired and weakly bound. Compared to the calculation with PKA1, one can see clearly that when the quasi-particle state  $1d_{5/2}$  is blocked in  $^{19}\text{C}$ , there dose not exist halo structure. In a word, blocking effect plays a crucial role in the halo occurrence for the odd-A nuclei.

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